Defense Technical Information Center Compilation Part Notice

ADP011144

TITLE: Compressor Stability and Control: Review and Practical Implications

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: Active Control Technology for Enhanced Performance Operational Capabilities of Military Aircraft, Land Vehicles and Sea Vehicles [Technologies des systemes a commandes actives pour l'amelioration des performances operationnelles des aeronefs militaires, des vehicules terrestres et des vehicules maritimes]

To order the complete compilation report, use: ADA395700

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP011101 thru ADP011178

UNCLASSIFIED

Compressor Stability and Control: Review and Practical Implications

James D. Paduano **Alan H. Epstein**
Gas Turbine Laboratory, Department of Aeronautics and Astronautics
Massachusetts Institute of Technology, Room 31-265
Cambridge, MA 02139 – 4307, USA

ABSTRACT

This paper discusses developments in axial compressor stability modeling over the last several years, and related work in active control of rotating stall and surge. Several major themes have emerged during this work. One theme is the interplay between hydrodynamic perturbations in axial compressors and instability inception. The former obey linearized dynamical equations, but their resonance and instability can trigger a variety of nonlinear events leading to violent oscillations in the compressor flow. An understanding of the key physical phenomena associated with stall inception, as opposed to those governing fully developed stall or surge, is critical to alleviating stall by design means or through active control. Another theme is the utility of actuators for understanding compressor stability. Active control work has prompted the installation of high-response forcing devices in compressors; even without feedback these have yielded much new information about compressor unsteady behavior. Finally, the paper reviews the methods and prospects for using active stabilization to extend the stable operating range of compressors, improving their surge margin and thus increasing overall reliability and performance. Experiments have progressed from laboratory scale demonstrations to full-scale rig and engine tests in about a decade. Competing theories about the physical mechanisms, the difficulties associated with stabilization, and the goals and control techniques for rotating stall have led to a rich research base on which compressor stability and control technology is being built.

1. INTRODUCTION

The concept of a 'smart engine', which utilizes augmented sensing, actuation, and computational power to increase the performance of its components, has captured the imagination of a variety of researchers since its introduction in the mid-1980's [1]. Fluid mechanicians, control specialists, experimentalists, nonlinear dynamicists, and mathematicians have all contributed ideas to the overall research mix. Concentration has been primarily on combustion control, and on stability and control of compressors and compression systems. The latter topic is the focus of this paper, where the phrase 'stability and control' is used in the same sense as in aircraft stability and control: understanding the equilibrium properties, the natural dynamics, and the influence of actuators is termed 'stability analysis', while augmentation of these properties through control mechanisms, usually applied through some sort of feedback loop, is called 'control'.

Compressor stability and control research parallels the early days of aircraft stability and control research in various ways. For instance, since certain regimes of operation are visited only infrequently (supersonic flight, hung stalls and spins are aircraft examples, very low flow rates and transient operation are compressor examples), various conjectures about the dynamics compete for precedence until enough information is amassed (and enough time has passed) that a workable consensus is reached. Also, in both cases instrumentation and in-operation (flight) test plays a critical role in verifying and refining conjectures. Finally, the lack of complete information often leads to the 'blind men and the elephant' syndrome, where either the perspective of the researcher or the limitations of the instrumentation in a particular experiment can bias the conclusions. Thus synthesis of all of the available research is required before a comprehensive picture can be constructed. This paper describes some of the competing views in compressor stability, and describes where some of the synthesis process has begun.

2. CHARACTERIZING THE DYNAMICS OF COMPRESSORS FOR CONTROL

The first challenge for creating the technology of stability and control of compressors is developing appropriate models. Here, as in any control problem, the fundamental requirement is to understand the key physical phenomena which drive the dynamic behavior. The focus of such characterization must be the stall inception process, as opposed to fully developed stall, for which many studies have been conducted (for a comprehensive review see [2]), but which exhibits different phenomena. Only after one develops at least a functional description of the processes at work during stall *inception* can effective control

Paper presented at the RTO AVT Symposium on "Active Control Technology for Enhanced Performance Operational Capabilities of Military Aircraft, Land Vehicles and Sea Vehicles", held in Braunschweig, Germany, 8-11 May 2000, and published in RTO MP-051.

architectures (sensors, actuators, control philosophy, and algorithms) be conceptualized, specified, and designed.

Fortunately a critical subset of the physics can be studied in low speed research compressors, and results in such compressors have carried over to full-scale devices. This approach creates a hierarchy of possible stall inception mechanisms, from those that appear in low speed compressors to those that appear in high speed and many-stage (*i.e.* more than three- or four-stage) machines.

A dialectic between two different points of view has dominated the discussion of physical mechanisms. For descriptive purposes, we take the thesis of this dialectic to be the following: long wavelength processes, or waves which span at least several blade pitches circumferentially, are the main physical entities that determine compressor stability properties. The antithesis is that short length scale events, which happen locally (within only 1 to 4 blade passages), are primarily responsible for stall inception. Although taken as the antithesis here, the associated physical explanation actually preceded the long length-scale hypothesis — here we wish to emphasize that it is antithetical to the concept of control (since control of short length scale events is difficult). Also, although this physical explanation dates back to the Emmons [3], it is a relatively new concept that rotating stall *inception* occurs in this way [4].

Waves as Precursors to Stall

The long length-scale description of rotating stall inception starts with a two-dimensional representation of the compression system as shown in Figure 1. Moore [5] developed a hydrodynamic stability analysis for this idealized system which was able to predict some of the basic characteristics of rotating stall. Moore and Greitzer [6] later developed this into a model which captured the interaction between rotating stall and surge.

The key physical processes which are represented in this model exist in low-speed as well as high speed rigs, and are the dominant factors in determining the rotation rate and stability properties of pre-stall waves [6-8]. The model incorporates the following assumptions (see Longley [9] for a review which contains the technical details):

1) Upstream and downstream flowfields impose linear impedance conditions upstream and downstream of the compressor.
2) The steady compressor characteristic is used as an empirical model of viscous processes in the compressor. The compressor's delivery of pressure rise in unsteady situations is modified by relatively simple models of unsteady loss, deviation, and blockage which retain two attributes:
   a) They remain empirical, tied directly to measured loss, deviation and blockage characteristics. These characteristics may be obtained from direct performance measurements in the compressor of interest, or be derived based on correlations or higher-order computational analyses [8, 10].
   b) Compressor blades are assumed to be infinitely closely spaced circumferentially (high solidity). Thus, only events whose circumferential profiles are smooth when compared to blade spacing are properly modeled.
3) The dynamics of the plenum, which acts as a mass storage device or 'spring', effects the mean flow through the system, coupling rotating stall and surge through changes in the compressor properties as a function of mean flow. Again, the nonlinear sensitivity of the compressor properties to mean flow is represented empirically.

The original manifestation of this model was derived by Moore and Greitzer [5, 6] assuming two dimensional (2D) incompressible flow in the ducts and compressor, and converted to a form suitable for control system analysis and design by Paduano *et al.* [11, 12] and Mansoux *et al.* [13]. If the flow in the ducts and blade rows is modeled as 2D, linearized, *compressible* flow, additional modes enter into the dynamic representation, although the basic features of the model are the same. Bonnaure [14] and Hendricks [15] developed a linearized compressible hydrodynamic stability model, which was converted to control theoretic form by Feulner [16]. This model has since been refined and validated against experimental data by Frechette [17] and Weigl [8, 18]. A three-dimensional, incompressible version of the model was developed by Gordon [19], and this has been extended to the compressible case by Sun [20].

In all of these models, the basic entity is a circumferentially sinusoidal wave of velocity perturbation, which rotates around the compressor annulus at a characteristic frequency, and either grows or decays as a function of time. The structure of this wave in the axial and radial direction depends on the assumptions of the model, but in every case one solves for the eigenmodes, which are sinusoidal circumferentially, and whose eigenvalues describe the rotation and growth rate of the modes. Presently we will give examples of velocity distributions near the compressor for various types of eigenmodes.

Several experimental investigations have focused on verifying that in fact compressors exhibit long length-scale perturbations which resonate and subsequently grow into rotating stall. The first of these were

conducted by McDougall [21], who showed that circumferentially rotating sinusoids of axial velocity perturbation preceded rotating stall inception in a low speed compressor. Garnier was able to measure these waves in low speed as well as high speed compressors [22]. A number of studies in high speed compressors followed [23-26], with varying conclusions depending on the instrumentation and data processing used.

In an attempt to come up with a more generally applicable description of stall inception, Tryfonidis *et al*. [7] applied identical processing to eight different high speed compressors, and showed two types of behavior, illustrated in Figure 2. Several compressors exhibited the resonance of sinusoidal waves prior to stall, with a resonance/rotation frequency of approximately half the rotor speed, as shown in a spectrogram in Figure 2a. This resonance corresponds to the eigenmode predicted by the Moore-Greitzer incompressible model. Where these waves were difficult to see in the raw traces or the spectral analyses, a different type of traveling wave was observed prior to stall. This is illustrated in Figure 2b, which is actually the same compressor at a higher rotation speed. In several compressors at 100% design speed, this wave traveled at exactly the rotor frequency, and grew in amplitude as the stall point was approached. It was postulated, and later verified in a single stage high speed compressor by Weigl, that the compressor can couple with the acoustic spinning modes [8] in the upstream and downstream ducts, and drive these modes to resonance or even instability. Operation near 100% design speed was found to be the critical speed in many compressors, due to an unfortunate (but not uncommon) coincidence of the acoustically coupled mode frequency and the rotor revolution frequency.

The compressor's ability to pump energy into acoustic waves is precisely the focus of the compressible stability model originally derived by Bonnaure and Hendricks [14, 15]. By accounting for compressibility in all of the ducts, the hydrodynamic analysis admits spinning acoustic modes in the upstream and downstream ducts. Figure 3 illustrates the difference between the incompressible flow solution in the upstream duct, which is the only solution coupled to the compressor in the Moore-Greitzer model, and a compressible flow solution which is coupled in by the compressible analysis. The ultimate mode shape of the system depends on the overall interaction between the upstream duct, the compressor, the downstream duct, and the boundary conditions. Figure 4a illustrates a typical compressible solution; Tryfonidis [7] and Weigl *et al*. [8] give further details on the characteristics of these modes.

Also shown in Figure 4 is the solution of an incompressible, three-dimensional hydrodynamic stability analysis [19]. Here although the mode shape is still sinusoidal circumferentially, radial variations in the mode shape are taken into account, as is the radial distribution of blade loading. Such modes may be important in low aspect-ratio compressors and fans.

Spike Stall Inception

In parallel to this research, a completely different model of stall inception was being developed. It was motivated by a picture originally drawn by Emmons *et al*. [3], and reproduced in Figure 5. The mechanism for stall inception was postulated by Day [4], who gave the following succinct explanation:

> "In a row of highly loaded blades, a minor physical irregularity, or flow nonuniformity, can result in momentary overloading and separation. This separation, or blockage, will restrict the flow through the blade passage and will therefore divert the incoming streamlines. On one side of the blockage the streamline diversion will cause increased incidence, and on the other side decreased incidence. The blade passage subjected to increased incidence... will therefore become stalled, while the one already stalled will unstall. The stall "cell" will thus propagate from blade to blade around the compressor... A cell like this would be called a disturbance of short length scale."

In this model it is postulated that while long length-scale, hydrodynamic modes exist in compressors, stall inception does not occur until the local mass flow through the blades is, at some spatial location, low enough that a small region of the annulus experiences catastrophic separation in the blade passage. This region then propagates via the mechanism described above, traveling and spreading rapidly into a fully developed stall or surge event. Features of this type of stall inception are:

1) Three-dimensionality. Separation tends to occur at the tip region of the blade, and the embryonic stall cell is initially concentrated in this region. The small circumferential and radial extent of the blockage causes a high rotation speed (approximately 70% of the rotor speed), which goes down as the size and extent of the stall cell increases (as rotating stall is initiated).
2) Nonlinearity. The 'spike' or 'pip' that develops is governed by separation and three dimensional flow redistribution phenomena [4, 25-28] both of which are nonlinear. Thus hydrodynamic stability analysis is not well suited to characterizing these flows.

3) Short time duration. The catastrophic nature of the separation event prevents any pre-stall signal ('precursor') from being detectable except immediately prior (on the order of a few rotor revolutions) to stall.

All of the features of short length-scale stall inception are detrimental to application of active control. Short, highly localized perturbations are difficult to detect unless sensors are placed very close to the location where they are occurring, and even then they appear on a given sensor only briefly. The lack of precursor information and the brief, nonlinear inception characteristics make linear controllers indefensible. In fact, Day's original control demonstration [29], which occurred just prior to the first long length-scale or 'modal' control demonstration, involved waiting for spikes to occur and then injecting air at the appropriate location to 'lead' the spike, thus canceling it in a nonlinear fashion and preventing it from developing into a stall cell. This approach would be impractical in a multi-stage environment, where one would have to determine the stage (or stages) at which spikes occur, and place actuators near those stages [30]. Changes in the operating point of the compressor invariably change the most highly loaded stage, so spike inception can move from one stage in the compressor to another.

Substantial experimental evidence for the importance of this form of stall inception has been amassed. The most detailed and convincing studies and reviews of data have been conducted by Day [25, 30], who has added considerable sophistication to the empirical description of these events. Figure 6 shows a typical stall inception example, which highlights the argument that spikes can sometimes lead into stall even when modes are present. Note that pre-stall traveling waves are evident in the data, but that the spike which ultimately develops into stall is not traveling at the same speed, nor is there any apparent relationship between the development of the stall cell and the pre-stall long length-scale waves. In some cases, waves are not evident at all, and stall inception consists only of the spike phenomenon. Silkowski [31] and Park [27] investigated the conditions under which spikes are initiated by rematching the downstream stages of a low speed compressor, and described some of the properties of the spikes.

Synthesis of Results

At this stage in axial compressor stall inception research, the question is not whether spikes exist or whether waves exist; both have been measured in many compressors and substantiated in great detail. The questions have to do instead with the importance of each to the stability and control of compressors. Under what conditions will a compressor exhibit spikes, and under what conditions waves? Which phenomenon sets the stability boundary of a compressor? How does compressor operating point effect these answers? Finally, what are the implications for control?

Recent developments have progressed toward answers about spikes versus modes. These developments are described by Camp and Day [28], who used experimental methods, and by Hoying [32], who gives a computational account and a postulates the fundamental mechanisms. Camp and Day showed that the first stage rotor in a four stage low-speed experimental compressor had an identifiable 'critical incidence' above which spikes occurred prior to stall inception. In this experiment, if the peak or zero-sloped portion of the overall compressor characteristic was reached before the first stage rotor reached its critical incidence, modal oscillations occurred, as predicted by long length-scale models. If, on the other hand, the critical rotor incidence was exceeded before resonance of the 'system' modes, then spikes appeared and transitioned the compressor into stall. Figure 7 shows the result of a number of experiments in which the first stage rotor incidence and compressor slope at stall inception were altered — either by restaggering the inlet guide vanes, or by rematching the compressor with incidence changes on the downstream stators. This plot clearly shows the connection between stall inception mechanism and rotor incidence.

Other developments also recognize the richness of the stall inception process. For instance, stall precursor identification is no longer based on searching for purely deterministic, linearized waves in time traces. Instead, nonlinear modeling and analysis of waves in compressors [13], as well as a realization of the highly stochastic nature of the environment, have led to the use of spectral methods to identify prestall disturbances [7]. Such methods are needed because stall inception, whether short or long length scale, involves nonlinear processes, so that the damping ratio of pre-stall eigenmodes may be small, but need not be zero at stall inception. Damping these eigenmodes can, however, significantly reduce the level of unsteadiness in a compressor, which may reduce the likelihood of spikes. Furthermore, nonlinear control techniques, discussed in Section 4, attempt to alter the global behavior of the system, so that the local (i.e. early inception) details may not be as important as the transition into large amplitude stall. During this transition, the larger size of the stall cell makes the dominant physical processes inertial; thus the nonlinear Moore-Greitzer model is sufficient to understand control of larger amplitude, developing stall cells. The

(perhaps prohibitive) penalty for such an approach appears to be larger requirements on the actuator strength.

Much of the understanding of rotating stall inception described in this section was gained or supported by experimental studies. These studies are distinguished from other rotating stall studies in two ways. First, as we mentioned above, they concentrate on the inception process, rather than fully developed stall. Second, many of these experiments have benefited from the existence of high speed actuators, which have provided a new look at compressor unsteady flows. Several actuated compressor experiments have been created, all with the primary goal of controlling rotating stall; each has also lent insight into the nature of stall inception. For instance, by stabilizing a mechanism that is postulated to lead to stall, and subsequently extending the operating range of a compressor, the postulated mechanism is proven to be the critical one. Details of the pre-stall dynamics are also best elucidated using high-response actuators.

3. ACTUATED COMPRESSORS FOR MODEL VALIDATION AND DEMONSTRATION OF CONTROL

This section reviews active control experiments that were conceptualized based on long wavelength concepts. These experiments have been focused on two objectives: verifying long wavelength models using system identification, and extending compressor operation through stabilization of hydrodynamic instabilities (see Figure 8). Approaches to rotating stall control which pursue different goals [33-35] often occurred in parallel to the research described in this section; this research will be presented in counterpoint in Section 4, rather than chronologically.

The original demonstrations of operating range extension via active stabilization of waves were by Paduano [36], followed soon after by Haynes [37] and Gysling [38]. All of these demonstrations were conducted in low speed compressors with clean inlet flow, using actuators with high bandwidth compared to the rotor frequency — on the order of 2.5 times the rotor frequency. In the work of Paduano and Haynes, 12 inlet guide vanes (IGVs) were modulated by servomotors mounted on the casing of the compressor. The actuators could independently set each IGV incidence at high bandwidth. This allowed a wave of actuation to be introduced in response to a wave of measured velocity perturbation - a feedback loop which stabilized the waves, allowing operation of the compressor below its normal stalling mass flow. The results of these demonstrations are reviewed by Greitzer *et al.* [39]. Gysling's approach [38] coupled an array of structural elements to the flow perturbations upstream. High-momentum air injection was modulated by flexible cantilevered plates ('reed valves') immediately upstream of the compressor face. The circumferentially distributed reed valves were deflected by the static pressure perturbations associated with prestall waves. This coupling created a new dynamical system with improved stability properties, without any sensing or computation (*i.e.* a dynamically tuned aero-structural system).

These demonstrations showed that in at least some low speed compressors, with clean inlet flow, small perturbation sinusoidal wave stability determines the stalling mass flow. The first sinusoidal circumferential harmonic goes unstable first, determining the stall point of the unmodified compressor. If this harmonic is stabilized, then the second harmonic goes unstable, at a reduced mass flow. By controlling the first and second Fourier harmonic, 8% to 20% increase in compressor operating range was achieved [36-37]. These demonstrations also showed the utility of system identification for model verification and refinement. See Haynes *et al.* [37], Longley [9], and Greitzer *et al.* [39] for a more complete review of this work and a discussion of the model refinements that resulted from forced response testing.

Once the possibility and utility of rotating stall stabilization were demonstrated, research began to focus on making active control more practical. Reducing the number of actuators and sensors required for control is one of the most compelling practical goals; this goal has motivated its own dialectic involving alternate control strategies (see Section 4). Two other critical practical issues are discussed here: inlet distortion and high speed implementation.

Implementing active control in the face of inlet distortion is of primary importance, since much of the current stall margin built into aircraft engines is there to maintain stability with inlet distortion. Van Schalkwyk [40] was the first to develop a control-theoretic model suitable for low-speed compressors with inlet distortion, and to implement controllers which stabilized the modes which arise when inlet distortion is present. Once again emphasis was placed not only on demonstrating control, but on demonstrating that the physical processes at work were well understood. The theoretical basis was the Hynes-Greitzer model [41], which relies on long length-scale assumptions, but which has very different behavior from the original Moore-Greitzer model, due to coupling of the spatial harmonics in the eigenmodes. This coupling of spatial harmonics renders the simple harmonic-by-harmonic control laws used in clean inlet flow much less effective — the eigenmodes of the system are no longer sinusoidal, and actuating a specific spatial sinusoid effects other modes of the coupled system.

Figures 9 and 10 illustrate the kind of steady and unsteady data which was obtained by van Schalkwyk in a low speed, 3-stage axial compressor with inlet distortion. Figure 9 shows the inlet distortion profile, comparing it to the prediction of the Hynes-Greitzer model. Clearly the physical processes are well accounted for in the modeling of the steady compressor response here. More importantly for control, the unsteady, input-output characteristics shown in Figure 10 are also well predicted by the theory, which relies only on steady-state compressor performance (total-to-static pressure rise and steady-state loss characteristics) and compressor geometry.

The current challenge for rotating stall modeling and control is high speed compressors. The challenges include modeling rotating stall inception when compressibility is important, effects which arise when many stages are present, distortion in the high speed environment, and development and implementation of suitable high speed actuators. Modeling high speed compressors was discussed in the previous section. The effects of many stages, and of distortion, are just beginning to be addressed — Day [30] and Freeman *et al.* [42] provide the most recent look at multistage compressors; this research will be discussed presently. Actuation development has been studied in the context of several projects, including [42-45]. We briefly review Berndt *et al.* [45] here to give a notion of the issues. The first high-speed demonstration of long wavelength mode stabilization was recently conducted by Weigl *et al.*[8, 18] using the actuators described below. This research will also be briefly described to illustrate the current state of the art.

The primary challenges in actuating high speed compressor rotating stall modes are the high bandwidth required, and the desire to have a large effect on the flowfield. Several researchers [29, 33, 34, 38, 42, 44, 45] have found that high speed valves which modulate airflow either into or out of the compressor are the most practical means to achieve high bandwidth and large effectiveness. Injection actuators were predicted to be the most effective based on low-speed analysis [43], so these have been developed for several applications. The valve's mass and internal volume as well as the placement and shape of the injector must be carefully designed to insure that high momentum air is introduced at the most beneficial location in a timely manner. Berndt [45] and Behnken [44] discuss design coupled with experiments to address these issues. Berndt discusses design of an actuator which was recently installed in a transonic single stage research compressor at NASA Lewis. These injectors have been shown to have a significant effect on both the pressure rise and stall flow coefficient, in part because the injected momentum is concentrated in the tip region of the compressor, which is known to have a strong influence on the overall compressor behavior. Similar results for steady injection were reported in [44]; for a detailed description of the use of this type of actuator for steady state performance improvement, see [62].

These actuators were used to perform thorough system identification and control tests in a NASA Lewis transonic single stage facility [45, 8]. While it was shown that the long wavelength approach is viable in this compressor, a more sophisticated implementation of the approach was required at 100% speed due to compressibility effects. Unlike the low-speed case in which each circumferential harmonic is a system eigenmode, each harmonic includes more than one lightly damped mode which can grow into rotating stall. Forced response testing identified several modes traveling at up to 150% of the rotor speed — these modes were found to be consistent with the 2D compressible hydrodynamic model discussed in Section 2. Robust dynamic control was required to stabilize the multiple modes which comprised the first three harmonic perturbations in the compressor — 0th (surge), 1st, and 2nd. Interestingly, surge and rotating stall occurred at almost the same mass flow in this compressor.

Figure 11 summarizes the results obtained, and demonstrates both the effectiveness of injection in steady state, and the additional improvement in stall margin that is obtained when active control is applied. As important as these results is the large amount of unsteady, forced-response data that was obtained, which provides a database against which the compressible model of rotating stall can be further developed and refined. This database represents a comprehensive look at high-speed compressor unsteady fluid mechanical characteristics. Such data can only be obtained using forced response measurements followed by application of system identification techniques.

Despite the success of these demonstrations, challenges still exist for implementation in a full-scale compressor with many stages. The most fundamental are those related to understanding the physical mechanisms; these have already been discussed. Day *et al.* [30], in a thorough examination of several compressors, concluded that in fact many stall inception mechanisms exist, and that they are so diverse, even in a single engine as it traverses its operational speed range, that an active control scheme which could handle them all is unlikely. D'Andrea, Behnken, and Murray [35] found that although the Moore-Greitzer model was sufficient to describe the behavior of their compressor, noise levels were too high to allow linear feedback concepts to be effective. Rolls-Royce, in a multi-year effort reported in Freeman *et al.* [42], also found that the stall inception details were not consistent with stabilization for range extension. Rather than

abandon active control of rotating stall, these researchers found alternate goals to pursue with active control. These goals, and how they relate to the goal of stabilization discussed in this section, are the subject of the next section.

4. ALTERNATIVE APPROACHES TO ROTATING STALL CONTROL

The debates concerning mechanisms for rotating stall inception, and the control demonstrations in ever more realistic environments, were described above under the following basic thesis: extension of the stable operating range of compressors is the goal of active control. Such extension allows compressor operation to be shifted closer to the no-control surge line (or beyond), allowing higher pressure ratios and rematching of the compressor design for higher compressor and/or overall cycle efficiency. Stall margin is maintained by active control's extension of the speed lines beyond their open-loop surge point.

The antithesis to the concept of range extension is this: maintenance of operating points near the peak of the compressor characteristic does not require range extension, and requires fewer actuators to implement. 'Maintenance' of an operating point means making it resist stall and surge in the face of disturbances, such as distortion, speed transients, and fuel spikes. If active control does this, then operability of the engine has been functionally enhanced at more desirable performance levels, regardless of the range extension which exists at mass flows below the operating point in question. Thus for instance the open-loop surge line could be transformed by active control into the operating line, not by range extension but by eliminating the tendency to surge along that line.

This subtle difference in goals was motivated by the desire to implement control with a single axisymmetric actuator - we will call this one-dimensional (1D) control. Liaw and Abed [46] conducted the seminal research in using 1D control for operability enhancement, although their interest was in how nonlinear control could be used to improve the 'bifurcation properties' of a simplified version of the Moore-Greitzer model first presented in [6]. The importance of this approach for operability enhancement was recognized by Badmus *et al.* [33], and subsequently demonstrated in a low speed compressor. Further enhancement and demonstration of the concept by Eveker *et al.* [34, 47] has been conducted in parallel to the 'range extension' research described in Section 3. It should also be mentioned that a form of 1D control was attempted by Ludwig and Nenni [48, 49] as early as 1976; these attempts suffered from lack of a theoretical basis as well as shortcomings in the testing equipment and procedures. These theoretical and technological shortcomings took another 20 years of research to overcome.

1D operability enhancement research has been conducted in the context of nonlinear control theory, introducing an entirely new set of researchers into the mix [50-55]. The centerpiece for this research is a three-state, nonlinear Galerkin approximation of the Moore-Greitzer incompressible model. This approximation was in fact introduced by Moore and Greitzer [6] for the purpose of elucidating the coupling between rotating stall and surge. McCaughan [50, 56] conducted a rigorous study of the model, in the context of bifurcation theory. This initial work showed that a very simple model exhibits the basic properties of surge and rotating stall inception, and their coupling, in a form which is simple enough to be analyzed by hand. Liaw and Abed [46] introduced control into the bifurcation analysis, postulating that by properly modulating a bleed valve in the compressor plenum, the peak of the compressor characteristic could be made resistant to disturbances.

The three states of the Galerkin Moore-Greitzer model are velocity in the compressor duct (Φ), pressure in the plenum (Ψ), and the amplitude of the 1st Fourier harmonic of velocity at the compressor face (A). The amplitude A is the Galerkin representation of the rotating stall cell amplitude. Note that in this model rotating stall is not an unsteady situation; in fact it is a *set of equilibria* along which A is non-zero[1]. Figure 12 shows the equilibria of MG3 and the open-loop stability properties. Note that there are four separate branches of equilibria, two of which are stable, and thus measurable in an open loop environment, and two which are unstable. The two unstable branches are the targets of the two approaches to control ('range extension' and 'operability enhancement'), as described below. The equilibrium to which the system settles is set by the intersection of the stable equilibrium branches with the throttle surface, $\Psi_T = (1/\gamma)\Phi^2$ (γ is proportional to the throttle area) which is independent of A and intersects either one or two of the stable solutions. The bottom inset in Figure 12 shows the migration of equilibria with γ, which is the most commonly used 'bifurcation parameter' for describing how the equilibria evolve.

In Figure 12, the two stable equilibrium branches are the points along the speed line, for which $A = 0$, and the rotating stall characteristic, along which A is large. As shown in the inset in Figure 12, as γ goes down in an uncontrolled compressor the system jumps from the no-stall branch to the in-stall branch in an abrupt way, which is undesirable. The hysteresis associated with recovery is also undesirable, as is the existence of two equilibria, one of which is rotating stall, at certain values of γ (in this case $1.4 < \gamma < 1.6$).

The first *unstable* equilibrium branch is the one along which $A = 0$. This is the extension of the compressor characteristic which has been discussed so far; stabilizing this set of equilibria is the goal of range extension. The second unstable equilibrium branch connects the peak of the compressor map and the rotating stall map; this is the focus of operability enhancement. If a control scheme can stabilize these equilibria, its existence may prevent the compressor from jumping directly between stable operation and fully developed rotating stall [34].

The inset in Figure 12 can also be interpreted as a bifurcation diagram with respect to a *disturbance* throttle area. The throttle characteristic is the same as described above, but here it represents effects which tend to undermine operability — changes in fuel flow, acceleration transients, etc. The fact that at a certain value of throttle area, the system jumps to a large amplitude rotating stall equilibrium, and that the area must be increase significantly before the system returns to normal operation, indicates that points near γ_{peak}, even if they are stable in the small-amplitude (linear) sense, tend to easily transition into rotating stall. Proof that these points do in fact have poor operability requires one to analyze the nonlinear stability properties of the equilibria; this has been done through simulation in [33], and in a more general context in [13] and [57].

Figure 13 shows the result of applying a feedback control of the following form:

$$\gamma_c = \gamma_o + K_A A^2$$

where γ_c is the area of a *controller* throttle valve, γ_o is its nominal area, and K_A is the controller gain. This control law does not stabilize the $A = 0$ branch of equilibria corresponding to range extension — such stabilization cannot be accomplished with a 1D controller. Instead, it stabilizes the $A \neq 0$ branch, along which A grows slowly and smoothly. The accompanying bifurcation diagram shows that with respect to the *disturbance* throttle, the system no longer exhibits a catastrophic jump into rotating stall. The compressor characteristic in Figure 13 indicates a subtlety associated with this change in the bifurcation characteristics: Although the disturbance throttle has closed down to a point well below the peak of the characteristic, the unsteady controller throttle opens partially, to maintain stability at a higher mass flow associated with the previously unreachable set of $A \neq 0$ equilibria.

The real utility of the controller is not measured by its ability to extend the mass flow range along this new branch of equilibria. Instead, it is measured by the resistance to instability of the peak of the compressor characteristic, which is the former surge line. Experiments by Eveker *et al.* [34, 47] have shown that transients on the disturbance throttle do not drive the system into rotating stall or surge when control is applied; without control the peak operating point has no resistance to disturbances at all. Thus control has effectively improved a surge margin-like operability measure, although it must now be quantified in a different way. Experimental demonstrations by Eveker *et al.* [47] showed that for systems which tend to surge (high B), the control law must be modified to balance rotating stall and surge requirements. Their controller adds feedback of mass flow acceleration in the compressor duct, taking the form:

$$\gamma_c = \gamma_o + K_A A^2 + K_{\dot{\Phi}} \dot{\Phi} .$$

Research into 1D control, because of its reliance on nonlinear control theory, has followed a somewhat separate path than range extension, leading to a different culture and different concepts. For instance, research has almost exclusively been restricted to the three state Galerkin representation, and very little work on alternate actuators has been conducted, although it can be shown that 1D control will not work using plenum bleed in full-scale compression systems [58, 59], and in fact success of the approach in large-scale experiments was achieved by changing the placement of the actuators [47]. In addition, the effects of distortion, being difficult to model in the Galerkin framework, have been ignored.

Very recent publications in rotating stall control represent a research community which is more aware of all of the possible goals and methods to achieve them. Synthesis of the competing concepts of range extension through linear control and maintenance of operating points through nonlinear control is occurring in several ways, creating a knowledge base of the important concepts to incorporate, and methods to overcome experimental difficulties that often arise in practice. Two main synthesizing concepts have emerged: 1) maintenance of desired operating points with a small number of actuators can often be achieved more effectively with alternate actuators *(i.e.* other than plenum bleed); 2) nonlinear analysis and disturbance rejection can be incorporated into range extension control schemes.

All of the successful recent implementations of active control reported to date have occurred using either bleed valves immediately downstream of the compressor [47], injectors upstream of the compressor [8, 35], or both [42, 60]. In some of these cases nonlinear control concepts akin to those described above were used; bifurcation concepts have clearly been important. But the use of plenum bleed valves, which is very prevalent in the nonlinear control literature, is not realistic and therefore does not appear in the experimental demonstrations. Future research into nonlinear control should be restricted to systems with actuators that have demonstrated utility in real systems.

A study of alternative actuation mechanisms and their relationship to nonlinear control has been conducted by D'Andrea *et al.* [35], Behnken *et al.* [44], Wang and Murray [54], and Yeung and Murray [60]. High-momentum, low flow inlet injectors, as well as downstream bleed valves, have been implemented in a low-speed rig and used in various configurations and combinations. Two main points can be derived from this work. First, the use of 2D actuation to alter the bifurcation properties of compressors constitutes a useful combination of the concepts described above: using Moore-Greitzer type modeling, the nonlinear bifurcation properties are altered not through 1D actuation, but through triggered 2D injection similar to that originally used by Day [29]. In [35] and [44], only three very simple (on-off) actuators were used, so that reduction of complexity was achieved as in 1D control, while demonstrating good nonlinear disturbance properties. The second point stressed in this research is that the large-amplitude nonlinear stability properties promised by bifurcation control literature cannot be obtained in practice. A much more realistic picture of the limitations of bifurcation control, under the constraints of actuator rate limits, saturation of the actuators, and noise, was developed in [54]. This work has helped to create a more balanced picture of the trades between 1D and 2D control.

Weigl *et al.* [8] also demonstrated that 2D control can be used to achieve beneficial nonlinear properties. By turning off the stabilizing controller, allowing rotating stall and surge waves to grow, and then reinitiating the controller, the nonlinear domain of attraction of the linearly stabilized operating points was demonstrated. Setiawan [61] performed a trade study to demonstrate the nonlinear properties of various controllers, concluding that in compression systems prone to surge, plenum bleed has the worst nonlinear properties. This work also makes the point that at least two separate measures of nonlinear robustness are important: 1) the stabilized system must resist downstream disturbances such as backpressuring with a disturbance throttle, fuel spikes, or acceleration transients; 2) the system must also resist upstream disturbances, specifically inlet distortion, in order to be viable in an operational engine environment. Freeman *et al.* [42] incorporated these requirements into their testing, and Protz [57] did the first experimental measurements of a controller's 'distortion tolerance', that is the combined ability of the controlled system to resist both upstream and downstream disturbances.

In the Rolls-Royce study of Freeman *et al.* [42], the concepts of alternate actuation and distortion tolerance were incorporated. A Viper engine's eight-stage compressor was outfitted with a recirculation mechanism that allowed bleed air from either the exit of the fourth stage or the last stage to be injected either at the fourth stage or at the inlet of the compressor. Six circumferentially distributed pipes recirculated the flow, actuated by high-response (300 Hz) hydraulic Moog valves. High response pressure transducers were placed, in circumferential arrays of five or six, at various stages. The system was driven toward the surge line by various methods: bleeding air into the combustor, fuel spiking, or by hot gas ingestion (which introduces severe distortion). Control strategies similar to those reported by Paduano [36] and Day [29] were tested, as well as a technique which commanded all of the valves to open whenever any third stage unsteady pressure signal exceeded an experimentally determined threshold level. The last technique, a 1D 'nonlinear' approach implemented with flow recirculation instead of plenum bleed, was found to increase the stable operating range by up to 25% in pressure rise, and was able to extend the stable operating range at all speeds and with each method of inducing stall. The philosophy of the 1D strategy was to sense stall inception and subsequently clear the stall cell before it fully developed, by introducing a stabilizing uniform recirculation. The steady-state benefit of recirculation was thus introduced in an unsteady manner only when necessary, reducing the overall recirculation requirements over a scheduled method.

Freeman *et al.* [42] contains a number of interesting discussions. The paper compares their most successful control system to the one originally tested by Ludwig and Nenni [48, 49], finding the concepts very similar although the more recent application was more refined. It also describes how inlet distortion can be addressed directly, by concentrating recirculation in a region which is appropriately phase shifted from the measured distortion. A discussion of the efficiency trade-offs between scheduled bleed, active recirculation, and 'ideal stall control' is also provided. Here the upshot is that by recirculating air, and by doing so only when necessary, significant efficiency improvements over currently used bleed schedules is

likely. The importance of injection modulation, as a high-bandwidth way to introduce the stabilizing effect of inlet injection, is also discussed.

In this work, as well as in the work of Weigl *et al.* [8] and Yeung *et al.* [60], the importance of actuation which improves the flow properties in the compressor was clearly demonstrated. Freeman *et al.* take an overall efficiency standpoint, concluding that bleed valves alone are both less effective and less efficient. Weigl utilized injection in the tip region of the compressor, improving the flow properties (in the region demonstrated to be critical in Section 2) to achieve the highest actuation leverage. Finally, Yeung *et al.* found that by steadily injecting a small amount of air upstream of their compressor, the bandwidth requirements for downstream bleed stabilization were significantly reduced. All of these studies demonstrate that understanding and actuating the detailed flow properties of the compressor is key to successful active control.

Comparison of the control schemes used shows that the best performance is usually achieved by introducing a stabilizing flow influence in an unsteady manner. In most cases this stabilizing influence can be introduced in a steady manner, achieving (usually less extensive) stall margin improvements without the complexity associated with modulated actuation. A penalty is usually associated with this, however, as either bleed or inlet injection involves bleeding high-pressure air from downstream of the compressor. By bleeding or injecting only when necessary, active control provides an automatic way of introducing corrective action with a lower overall efficiency penalty. The trade between efficiency, surge margin, and complexity is a difficult one, which will fall in favor of implementing control only through very careful design and implementation.

5. POTENTIAL BENEFITS OF ACTIVE CONTROL

Active compressor control was a term originally intended to refer to the use of feedback control to extend the stable operating range of gas turbine compression systems Based on the discussions presented here, and on other ongoing work, it is clear that it now encompasses a wide range of technical approaches and goals. This includes feedback control to extend the operation range (active stabilization), feedback control to enhance robustness to disturbances (to permit operation closer to the no control surge line), change to the steady state operating point upon the detection of disturbances (opening bleed valves, restaggering stators, etc.), and even the use of high frequency response measurements within the compressor as a diagnostic and maintenance aid. The cost of these approaches vary considerably. By cost we refer to such things as the number, authority, and bandwidth of the actuators and sensors required, the computer power needed, engine performance penalties incurred, and overall weight. These costs are balanced against the benefits realized from the inclusion of active control in an engine design. It is the balance that is the topic of this section.

Compressor stability is really a singular state in the sense that a compressor is stable or it is not. The stability margin criteria commonly employed are used to account for stability "threats" encountered over the operating life of an engine. Some threats vary relatively rapidly with time because they are operating condition related, such as inlet distortion, engine transient, and altitude (Reynolds number) effects. Other threats have very long time constants such as those related to unit to unit manufacturing variations and long term engine aging. The threats are typically expressed in terms of a stall margin, a percentage pressure rise between the nominal surge line and the steady state engine operating line. Thus, the benefits of active control have often been expressed as a percentage increase in the surge margin. However, surge margin, as such, is a fairly crude measure of stability for a dynamical system as complex as a modern aircraft engine. Therefore, to regard active control mainly in terms of stall margin extension may mask some potential advantages.

Innovations such as active control can regarded in two ways. The first is how this new technology might allow us to do what we do now better. For most applications, better implies lower overall lifecycle cost for an airline or weapons systems. Alternatively, the new technology can be enabling, i.e. it can let us do something that either we could not do before, or let us do it in a new, significantly improved manner (stealth technology might be an example here). First, we will consider current stability practice. Modern engines ensure stability with steady geometry included flow variations imposed through a combination of passive design features and fuel control scheduled geometry changes. The primary passive design feature is multiple spool compressors. Scheduled steady state geometry changes include bleed valves, variable geometry stators, and exhaust nozzle are manipulation. Current approached are not without cost. In the case of multiple spools, the cost is mechanical complexity and increase weight an manufacturing cost. (Note that high bypass turbofans require either 2 spools or a gear to keep the fan drive turbine to reasonable size, but this is not true for low bypass ratio military engines.) Bleeds can be costly because loss of compressed air decreases compressor efficiency and so increases overall fuel consumption. (One informal

estimate is that the operator of a large commercial aircraft may spend $100,000 per year on stability bleed air fuel.) Variable stator mechanisms are relatively costly and heavy, adding about 50% to the weight of a stage. Also the stator settings required for stable operation are often not those for maximum efficiency.

Other penalties associated with current practice may be more subtle. Inlet distortion can fall into this category. For example, in a modern tactical aircraft application with a fixed geometry inlet, maximum inlet distortion is often encountered during rotation on takeoff. To reduce this distortion to a level no higher than that found during other portions of the flight envelope (such as maneuver), aircraft designers may oversize the inlet capture area relative to that required at cruise. This results in increased spillage drag at cruise. Thus this short time, single point stability requirement penalizes most of the aircraft flight regime with a concomitant increase in fuel consumption and decrease in range. One estimate place this drag penalty as equivalent to an 8% decrease in range. An additional benefit accrues if the increased stable operating range permits the engine to operate at lower mass flow at constant power during takeoff. In this case, the entire inlet can be downsized accordingly, to the benefit of inlet weight and drag.

Active compressor control can also be an enabling technology in that it can permit configurations that are not otherwise achievable with significantly downrated engines (which render the concept unattractive). One example might be top mounted inlets for tactical aircraft which require larger maneuver envelopes than the B-2 and a larger tolerance for inlet distortion. A somewhat different example is very high bypass ratio turbofan engines above about 12:1. The optimum fan pressure ratio falls with increasing bypass ratio. Once the pressure ratio is so low that the fan nozzle is no longer choked, the fan operating point shifts with flight condition and power setting so as to reduce the fan stall margin below requirement. Without some type of stability augmentation then variable geometry would be needed, either a variable area fan nozzle or a variable fan pitch.

6. REFERENCES

1. Epstein. A. H., Fowcs-Williams, J. E., and Greitzer, E. M., "Active Suppression of Aerodynamic Instabilities in Turbomachines," *Trans. AIAA J. of Prop. and Power*, Vol. 5, No. 2 (1986) 204-211.
2. Pampreen, R. C., *Compressor Surge and Stall*, Concepts ETI, Norwich VT (1993).
3. Emmons, H. W., Pearson, C. F., and Grant, H. P., "Compressor Surge and Stall Propagation," *Trans. of the ASME*, Vol. 79 (1955).
4. Day, I.J., "Stall Inception in Axial Flow Compressors," *ASME J. of Turbomach.*, Vol. 115 (1993) 1-9.
5. Moore, F. K., "A Theory of Rotating Stall of Multistage Compressors, Parts I-III," *ASME J. of Engineering for Power*, Vol. 106 (1984) 313-336.
6. Moore, F. K. and Greitzer, E. M., "A Theory of Post-Stall Transients in Axial Compression Systems, Part I - Development of Equations, and Part II - Application, " *ASME J. of Engineering for Gas Turbines and Power,* Vol. 108 (1986) 68-97.
7. Tryfonidis, M., Etchevers, O., Paduano, J. ., Epstein, A. H., and Hendricks, G. J., "Pre-Stall Behavior of Several High-Speed Compressors," *ASME J. of Turbomachinery*, Vol. 117, No. 1 (1995) 62-80.
8. Weigl, H. J., Paduano, J. D., Frechette, L. G., Epstein, A. H., Greitzer, E. M., Bright, M. M., and Strazisar, A. J., "Active Stabilization of Rotating Stall in a Transonic Single Stage Axial Compressor," 97-GT-411, ASME Turbo Expo '97, Orlando. (1997).
9. Longley, J. P., "A Review of Non-Steady Flow Models for Compressor Stability," ASME Paper 93-GT-17, 1993 ASME Turbo Expo, Cincinnati, (1993).
10. Spakovszky, Z. S., "Simulation of Engine Clearance Effects on Compressor Dynamic Behavior During Acceleration Transients," Dipl. Masch. Ing. ETH Thesis (1997).
11. Paduano, J. D., Valavani, L., Epstein, A. H., Greitzer, E. M. and Guenette, G. R., "Modeling for Control of Rotating Stall," *Automatica,* Vol. 30, No. 9 (1994) 1357-1373.
12. Paduano, J. D., Valavani, L., and Epstein, A. H., "Parameter Identification of Compressor Dynamics During Closed-Loop Operation," American Control Conference, June, Boston (1991).
13. Mansoux, C. A., Gysling, D. L., Setiawan, J. D., and Paduano, J. D., "Distributed Nonlinear Modeling and Stability Analysis of Axial Compressor Stall and Surge," American Control Conference, July, Baltimore (1994).
14. Bonnaure, L. P., "Modeling High Speed Multistage Compressor Stability," M. S. Thesis, MIT Department of Aeronautics and Astronautics (1991).
15. Hendricks, G. J., Bonnaure, L. P., Longley, J. P., Greitzer E. M., Epstein A. H., "Analysis of Rotating Stall Onset In High-Speed Axial Flow Compressors," AIAA paper 93-2233, 29th Joint Propulsion Conference, Monterey (1993).

16. Feulner, M. R., Hendricks, G. J., and Paduano, J. D., "Modeling for Control of Rotating Stall in High Speed Multi-Stage Axial Compressors," 94-GT-200, ASME Turbo Expo '94, June 13-16, The Hague, Netherlands (1994).
17. Frechette, L. G., "Implications of Stability Modeling for High-Speed Axial Compressor Design," Master's Thesis, MIT Department of Aeronautics and Astronautics (1997).
18. Weigl H. J., "Active Stabilization of Rotating Stall and Surge in a Transonic Single Stage Axial Compressor," Ph.D. Thesis, MIT Department of Aeronautics and Astronautics (1997).
19. Gordon, K., personal communication.
20. Sun, X. F., "Three-Dimensional Compressible Flow Stability Theory of Rotating Stall," BUAA Technical Report BH-B4765, Beijing University of Aeronautics and Astronautics, Department of Jet Propulsion (1996).
21. McDougall, N. M, Cumpsty, N. A., and Hynes, T. P., "Stall Inception in Axial Compressors," *ASME J. of Turbomachinery*, Vol. 112 (1990) 116-125.
22. Garnier, V. H., Epstein, A. H., and Greitzer, E. M., "Rotating Waves as a Stall Inception Indication in Axial Compressors," *ASME J. of Turbomachinery*, Vol. 113 (1991) 290-301.
23. Hoying, D. A., "Stall Inception in a Multistage High Speed Axial Compressor," 29th Joint Propulsion Conference, Monterey (1993).
24. Inoue, M., Kuroumaru, M., and Ando, Y., "Detection of a Rotating Stall Precursor in Isolated Axial Flow Compressor Rotors," *ASME J. of Turbomachinery*, Vol. 113 (1993) 281-287.
25. Day, I. J., and Freeman, C., "The Unstable Behaviour of Low and High Speed Compressors," *ASME J. of Turbomachinery*, Vol. 116, No. 2 (1994) 217-225.
26. Anderton, J. F., King, P. I., and Copenhaver, W. W., "Stall Analysis of High-Frequency Data for Three Swept-Blade Compressor Rotors," in *Proceedings of SPIE*, Volume 2494, Orlando (1995).
27. Park, H. G., "Unsteady Disturbance Structures in Axial Flow Compressor Stall Inception," Master's Thesis, MIT Department of Aeronautics and Astronautics (1994).
28. Camp, T. R., and Day, I. J., "A Study of Spike and Modal Stall Phenomena in a Low-Speed Axial Compressor," 97-GT-526, ASME Turbo Expo '97, Orlando (1997).
29. Day, I. J., "Active Suppression of Rotating Stall and Surge in Axial Compressors," *ASME J. of Turbomachinery*, Vol. 115 (1993) 40-47.
30. Day, I. J., Breuer, T., Escuret, J., Cherrett, M., Wilson, A., "Stall Inception and the Prospects for Active Control in Four High Speed Compressors," 97-GT-281, ASME Turbo Expo '97, Orlando.
31. Silkowski, P. D., "Measurements of Rotor Stalling in a Matched and Mismatched Multistage Compressor, GTL Report No. 221, Gas Turbine Laboratory, Mass. Inst. of Technology (1995).
32. Hoying, D. A., "Blade Passage Flow Structure Effects on Axial Compressor Rotating Stall Inception, Ph.D. Thesis, MIT Department of Aeronautics and Astronautics (1996).
33. Badmus, O. O., Chowdhury, S., Eveker, K. M., Nett, C. N., and Rivera, C. J., "A Simplified Approach for Control of Rotating Stall Part I: Theoretical Development and Part II: Experimental Results," AIAA 93-2229 and AIAA 93-2234, 29th Joint Propulsion Conference, Monterey (1993).
34. Eveker, K. M., Gysling, D. L., Nett, C. N., and Sharma, O. P., "Integrated Control of Rotating Stall and Surge in a Low speed Axial Compression System," in *Proceedings of SPIE*, Volume 2494, Orlando (1995) 17-18.
35. D'Andrea, R., Behnken, R. L., Murray, R. M., "Active Control of Rotating Stall via Pulsed Air Injection: A Parametric Study on a Low Speed, Axial Flow Compressor," in *Proceedings of SPIE*, Volume 2494, Orlando (1995) 152-165.
36. Paduano, J. D., Epstein, A. H., Valavani, L., Longley, J. P., Greitzer, E. M., and Guennette, G. R., "Active Control of Rotating Stall in a Low Speed Axial Compressor," *ASME J. of Turbomachinery*, Vol. 115, No. 1 (1993) 48-56.
37. Haynes, J. M., Hendricks, G. J., and Epstein, A. H., "Active Stabilization of Rotating Stall in a Three-Stage Axial Compressor," *ASME J. of Turbomachinery*, Vol. 116 (1994) 226-239.
38. Gysling, D. L., Dugundji, J., Greitzer, E. M., and Epstein, A. H., "Dynamic Control of Compressor Surge using Tailored Structures," *ASME J. of Turbomachinery*, Vol. 113 (1991) 710-722.
39. Greitzer, E.M., Epstein, A.H., Guenette, G., Gysling, D., Haynes, J., Hendricks, G.J., Paduano, J., Simon, J., and Valavani, L., "Dynamic Control of Aerodynamic Instabilities in Gas Turbine Engine," *Steady and Transient Performance Prediction of Gas Turbine Engines,* AGARD-LS-183 (1992).
40. van Schalkwyk, C. M., Paduano, J. D., Greitzer, E. M., and Epstein, A. H., "Active Stabilization of Axial Compressors with Circumferential Inlet Distortion," 97-GT-279, ASME Turbo Expo '97, Orlando (1997).

41. Hynes, T. P. and Greitzer, E. M. "A Method of Assessing Effects of Circumferential Flow Distortion on Compressor Stability," *ASME J. of Turbomachinery*, Vol. 109 (1987) 371-379.
42. Freeman, C., Wilson, A. G., Day, I. J., and Swinbanks, M. A., "Experiments in Active Control of Stall on an Aeroengine Gas Turbine," 97-GT-280, ASME Turbo Expo '97, Orlando (1997).
43. Hendricks, G. J., and Gysling, D. L., "A Theoretical Study of Sensor-Actuator Schemes for Rotating Stall Control," 28th Joint Propulsion Conference, Nashville, TN (1992).
44. Behnken, R. L., Leung, M., and Murray, R. M., "Characterizing the Effects of Air Injection on Compressor Performance for Use in Active Control of Rotating Stall," 97-GT-316, ASME Turbo Expo '97, Orlando (1997).
45. Berndt, R. G., Weigl, H. J., Paduano, J. D., and Epstein, A. H., "Experimental Techniques for Actuation, Sensing and Measurement of Rotating Stall Dynamics in High Speed Compressors," in *Proceedings of SPIE*, Volume 2494, Orlando (1995) 166-185.
46. Liaw, D. C., and Abed, E. H., "Active Stabilization of Rotating Stall: A Bifurcation-Theoretic Approach," Second IFAC Nonlinear Control Symposium, Bordeaux, France (1992).
47. Eveker, K.M., Gysling, D.L., Nett, C.N., and Sharma, O.P., "Integrated Control of Rotating Stall and Surge in High-Speed Multi-Stage Compression Systems," 97-GT-352, ASME Turbo Expo '97, Orlando (1997).
48. Ludwig, G. R., and Nenni, J. P., "A Rotating Stall Control System for Turbojet Engines," ASME Paper 76-GT-115 (1976).
49. Ludwig, G. R., and Nenni, J. P., "Tests of an Improved Rotating Stall Control System on a J-85 Turbojet Engine," ASME Paper 80-GT-17, Gas Turbine Conference and Products Show, New Orleans (1980).
50. McCaughan, F. E., "Application of Bifurcation Theory to Axial Flow Compressor Stability," *ASME J. Turbomachinery*, Vol. 3 (1989) 426-433.
51. Adomaitis, R. A., and Abed, E. H., "Local Nonlinear Control of Stall Inception in Axial Flow Compressors," AIAA Paper 93-2230, 29th Joint Propulsion Conference, Monterey (1993).
52. Ballieul, J., Dahlgren, S., and Lehman, B., "Nonlinear Control Designs for Systems with Bifurcations with Applications to Stabilization and Control of Compressors," Proc. 34th Conference on Decision and Control, New Orleans, LA (1995) 3062-3067.
53. Lin, F., "On the Practical Stability and Its Application to Nonlinear Control of Surge," ASME Paper 96-GT-512, 1996 ASME Turbo Expo (1996).
54. Wang, Y., and Murray, R. M., "Effects of Noise, Magnitude Saturation, and Rate Limits on Rotating Stall Control," 36th IEEE Conference on Decision and Control (1997).
55. Krstic, M., Protz, J. M., Paduano, J. D., and Kokotovic, P. V., "Backstepping Designs for Jet Engine Stall and Surge Control," Proceedings of the 34th Conference on Decision and Control, New Orleans, LA (1995) 3049-3055.
56. McCaughan, F. E., "An Analytical and Numerical Study of Axial Flow Compressor Instability," *ASME J. of Turbomachinery*, Vol. 3 (1989) 434-441.
57 Protz., J. M., Master's Thesis, MIT Department of Aeronautics and Astronautics (1997).
58. Simon, J. S., Valavani, L., Epstein, A. H., and Greitzer, E. M., "Evaluation of Approaches to Active Compressor Surge Stabilization," *ASME J. of Turbomachinery*, Vol. 115 (1993) 57-67.
59. Wang, H. H., Krstic, M., Larsen, M., "Control of Deep-Hysteresis Aeroengine Compressors, Part I and II," American Control Conference, Albuquerque (1997).
60. Yeung, S. and Murray, R. M., "Reduction of Bleed Valve Bandwidth Requirements for Control of Rotating Stall using Continuous Air Injection," Conference on Control Applications, East Hartford (1997).
61. Setiawan, J. D., "Distortion Tolerance of Stall/Surge Controllers in Axial Compression Systems," Master's Thesis, MIT Department of Aeronautics and Astronautics (1996).
62. Suder, K.L., Hathaway, M.D., Thorp, S.A., Strazisar, A.J., and Bright, M.B., "Compressor Stability Enhancement Using Discrete Tip Injection," ASME Turbo Expo, May 8-11, Munich (2000).

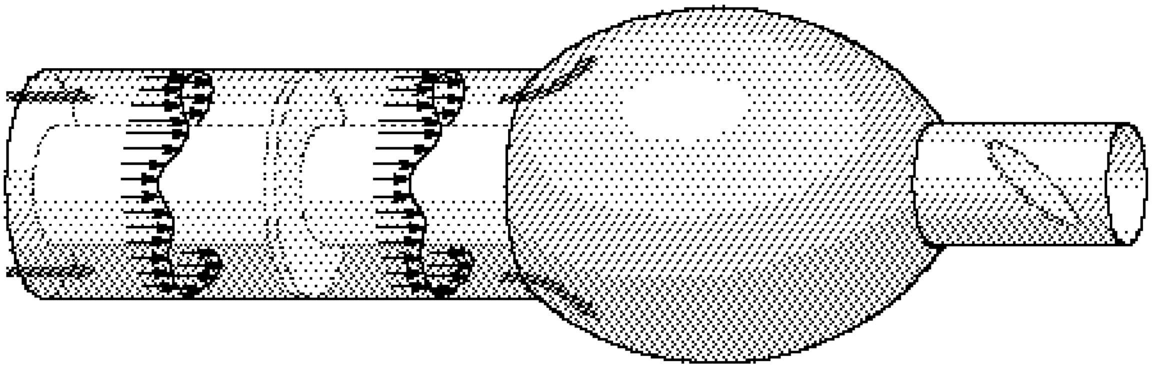


Figure 1 - Schematic of a compression system, including upstream and downstream ducts, compressor model, plenum, and throttle.

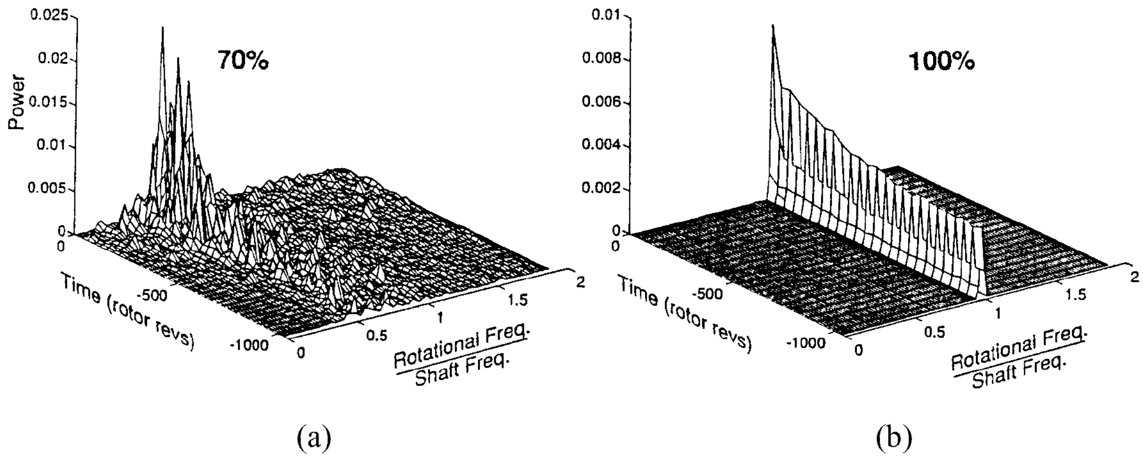


Figure 2 - Spectrograms of two different precursor events, immediately prior to stall in a high-speed compressor. (a) 70% design speed; (b) 100% design speed. From Tryfonidis [6].

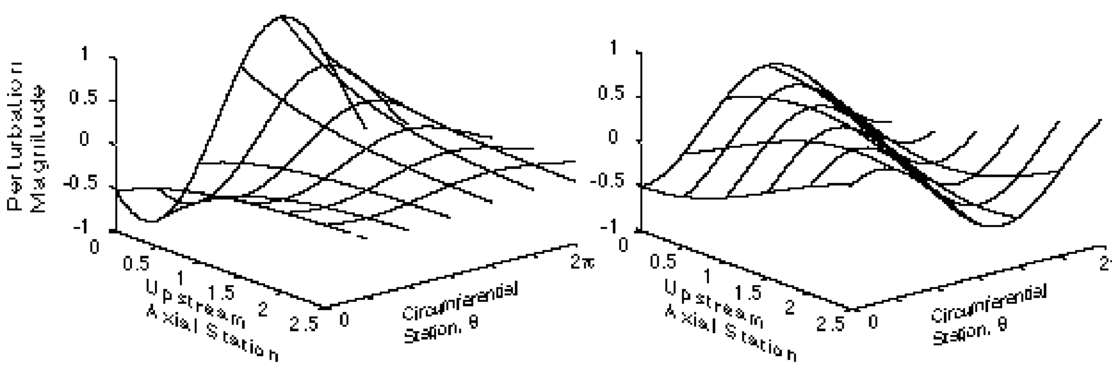
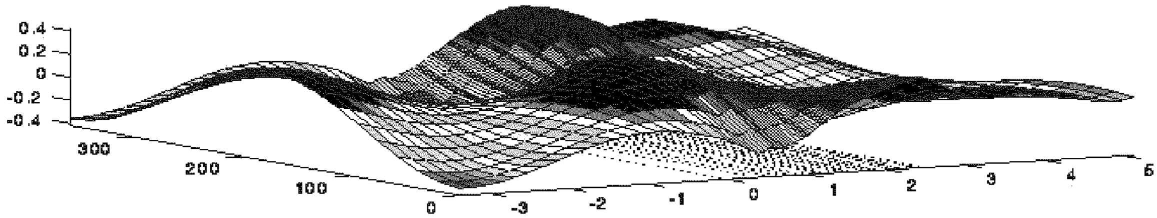
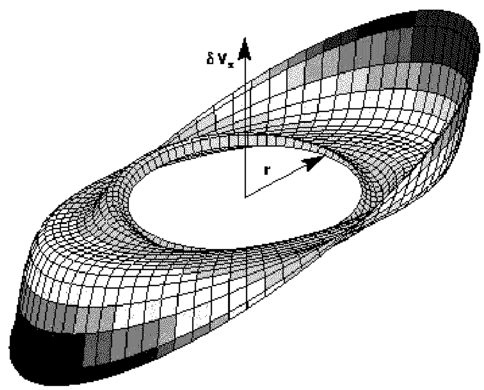


Figure 3 - Examples of upstream axial velocity distribution for incompressible (left) and compressible (right) 2D eigenmodes.



(a)



(b)

Figure 4 - Examples of eigenmode shapes in two hydrodynamic stability models.
(a) Compressible 2D model, (b) incompressible 3D model.

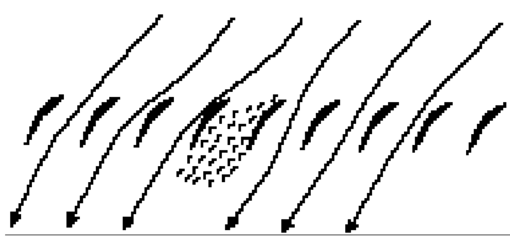


Figure 5 - Sketch of short-length scale rotating stall event. From Day [25].

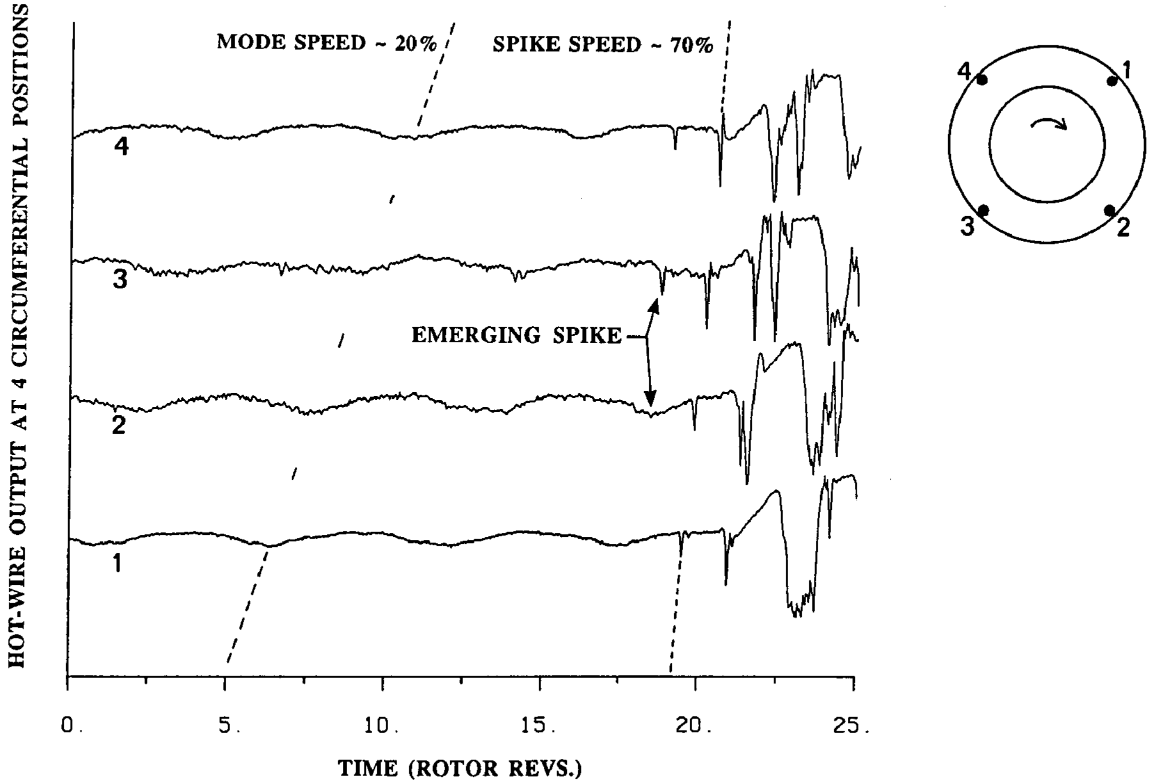


Figure 6 - Short length-scale event in a low speed compressor, from Day [25].

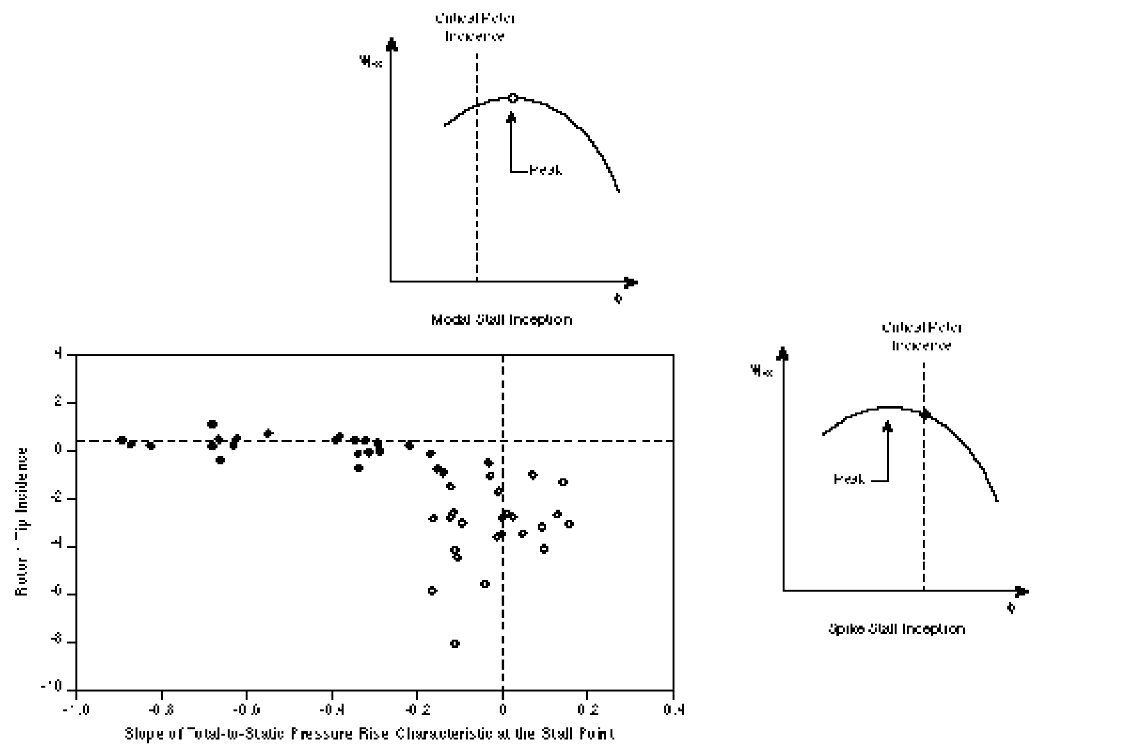


Figure 7 - Experimental Results from Camp and Day [31], showing the criticality of incidence in on the rotor of a four stage compressor.

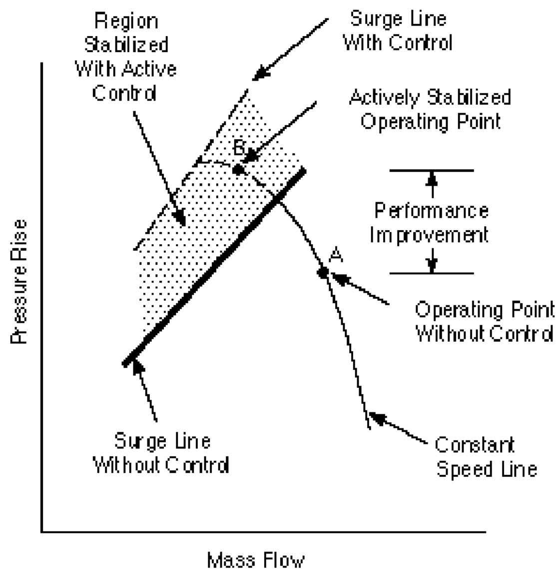


Figure 8 - Goal of active compressor operating range extension via stabilization.

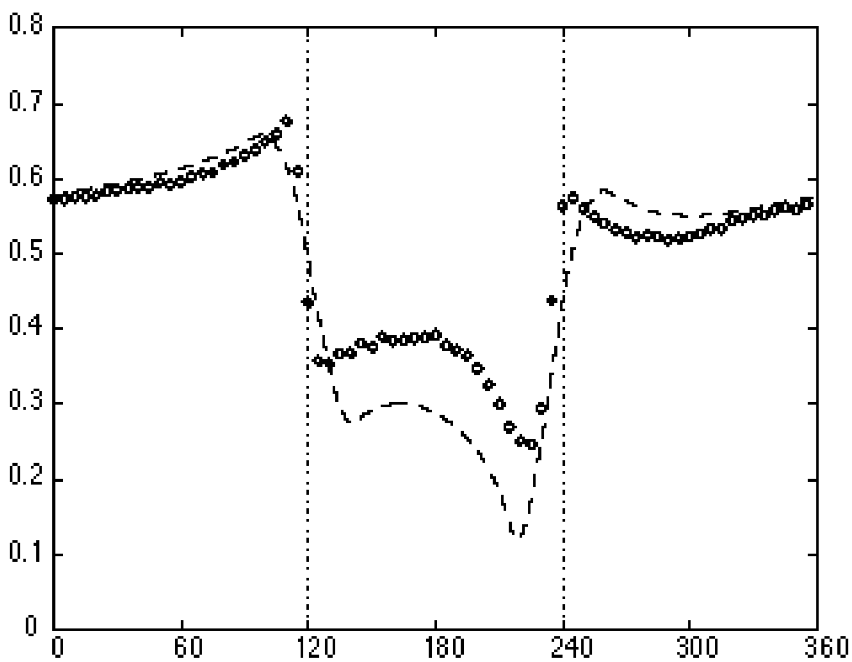


Figure 9 - Comparison of theoretical (dashed) and measured (circles) velocity profile due to an inlet distortion. From van Schalkwyk et al. [40].

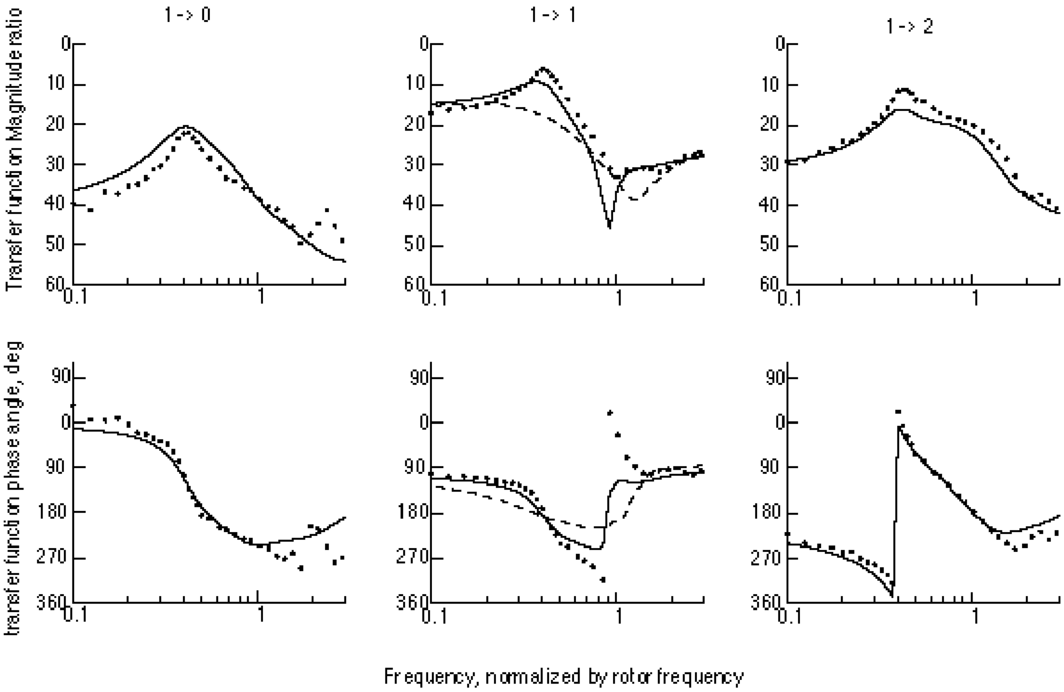


Figure 10 - Transfer function from first Fourier coefficient of inlet guide vane deflection to 0th, 1st, and 2nd Fourier coefficient of axial velocity. Data taken with 1.9 dynamic head inlet distortion (circles) and compared to theory (lines) dashed line represents undistorted flow prediction. From van Schalkwyk et al. [40].

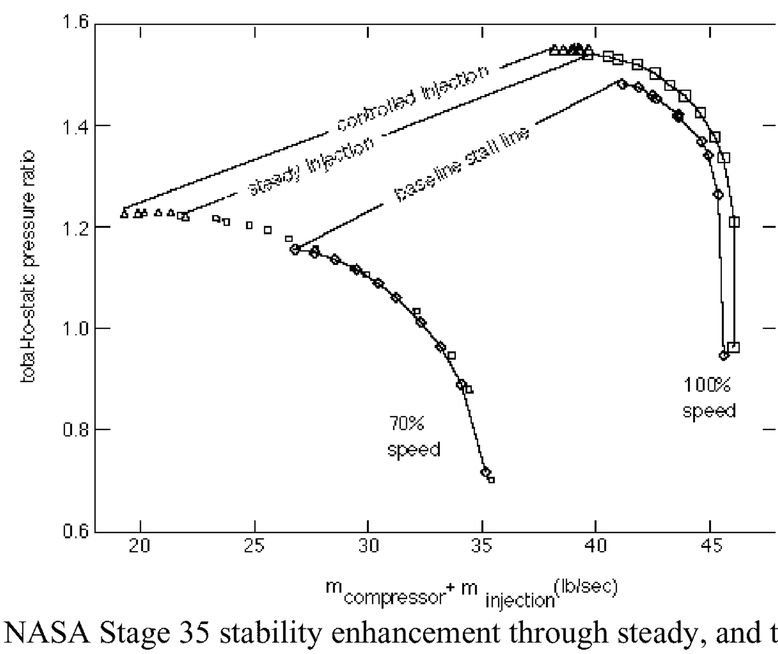


Figure 11 - NASA Stage 35 stability enhancement through steady, and through steady plus feedback-controlled unsteady inlet injection. Mean rate of mass injection was 1.57 lb/sec.

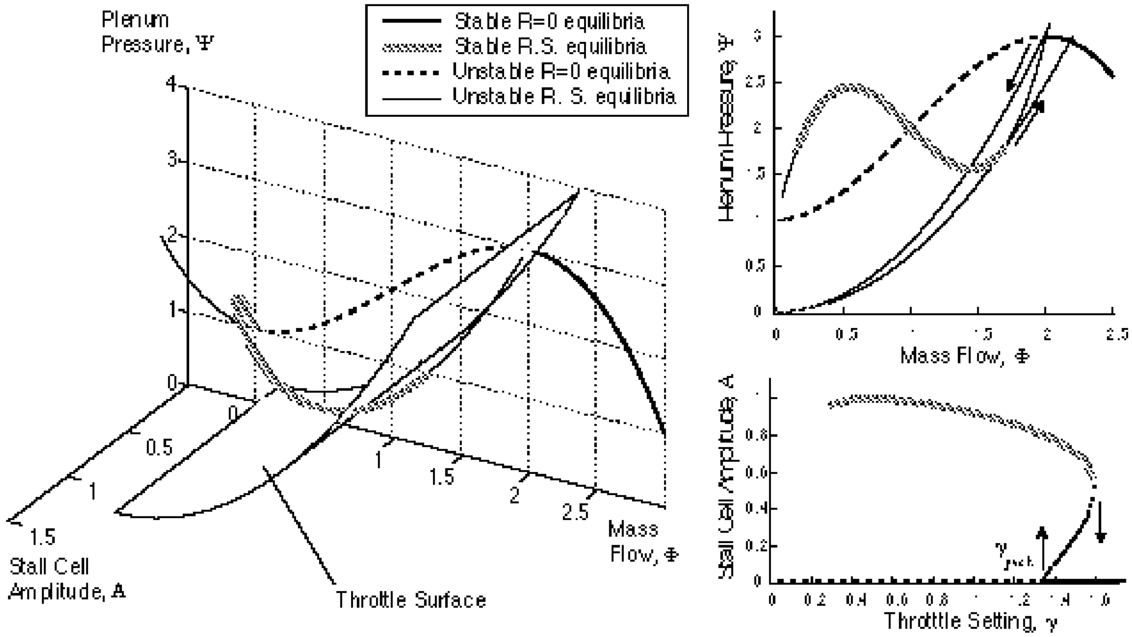


Figure 12 - Equilibria of the three-state Moore-Greitzer model.

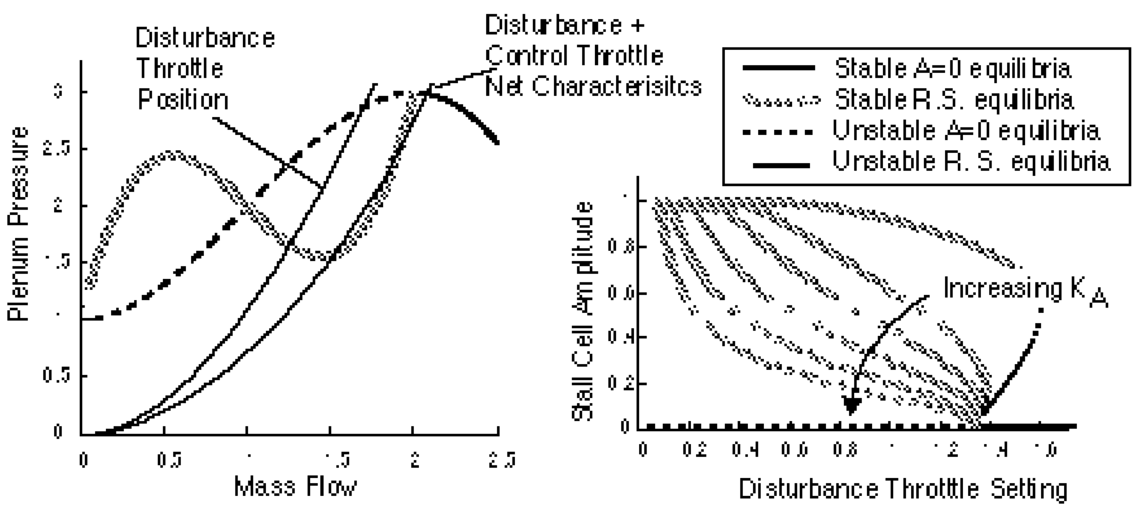


Figure 13 - Effect of plenum bleed feedback on equilibrium properites.

Paper 1, J. D. Paduano

Question (S. Candel, France)

Could you give more information on how you are using a single sensor to detect stall/surge?

Reply

Several methods exist in the literature to identify pre-stall signatures on a single sensor (usually wall static pressure) placed in an axial compressor (usually near the leading edge of the rotor, or over the rotor of the most critical blade row, which is often the first). These methods involve wavelet transformations, but methods based on the theory of time series analysis for nonlinear dynamical systems have also been employed. Often the methods are tailored for the specific data set of the compressor under consideration, and at this point there does not appear to be an approach that works universally.

In the application cited in my talk, the spectrogram (power spectral density computed over a moving window, so that it is time dependent) of the pressure transducer is computed, and the intensity of the peak signal at 1E is computed. Our modeling showed that there is an eigenvalue very near the 1E excitation, and that the stability of this eigenvalue is indicative of the instantaneous stall margin during transients. It was found that engine deterioration degrades transient stall margin, and that experimental results, model calculations and real-time 1E indicators all capture this effect. See the *J. Turbomachinery*, Vol 122 paper by Spakovsky *et al.*, July 2000, for more details.

Question (T. Lewis, USA)

Regarding the flow injection/recirculation for stabilization testing by NASA and MIT: was the internal air source the discharge of the compressor under test, or some external source? The concern would be the destabilizing effects of hot air injection and whether these effects would outweigh the measured stability improvements.

Reply

Tests to date have used cool ("shop") air injected from an external supply. Our understanding of the effect of hot air recirculation is that

a) as long as the injectors remain choked, no new instabilities will be introduced;
b) the effectiveness of the injector will be reduced, e.g., because the fluid density is reduced, affecting $\overline{V}_x / U_{tip}$;
c) the injectors must be rated for higher temperatures, a practical matter.

Question (M. Richman, USA)

Could you comment on the ability of the General Dynamics eddy current sensor to detect the precursor to stall versus a pressure sensor?

Reply

This depends on the blade stiffness. For core compressor stages (where the blades are stiff in twist), the eddy current sensor would not perform as well. For fan stages (lower stiffness), the eddy current sensor is more likely to be effective. The rotating stall cell will almost surely be detectable in either case, but the small amplitude stall precursors may be more difficult. This has yet to be demonstrated.